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Estimation of Water Demands Using Deficit Analysis

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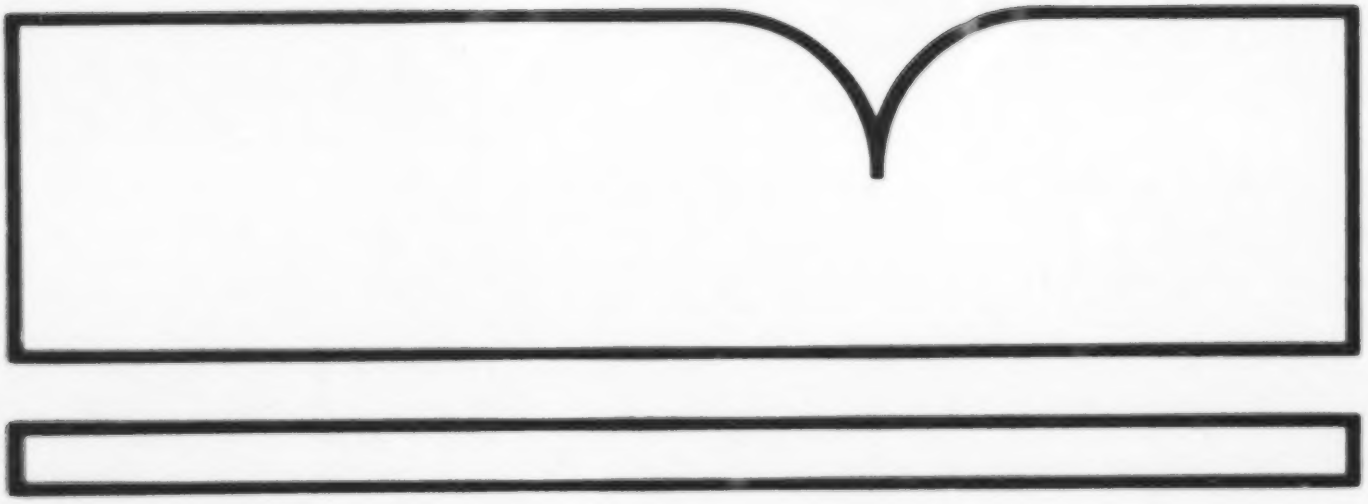

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16. ABSTRACT

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ESTIMATION OF WATER DEMANDS USING DEFICIT ANALYSIS

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ABSTRACT: Competition for water among governmental entities with common river systems has become increasingly fierce. This competition will no doubt become even more fierce as populations continue to grow and become increasingly dispersed. One of the major issues involved in water resource availability is the construction of reservoirs to provide continuous and dependable water supply. Historically, the approach to reservoir "sizing" is based on comparing the lowest historical stream flow against the highest water demands anticipated. More recently stochastic techniques have been used to estimate water yield. This paper uses a technique, "deficit analysis," that matches available flow versus actual and/or projected demands. If demand exceeds available flow, a deficit occurs that must be satisfied by flow augmentation or reservoir capacity. Standard techniques such as the Ripple procedure or routing techniques can reveal total amounts of water required. By studying the shape and timing of deficits important additional design information can be gained. The technique is applied in a case study context to reservoir selection in the Washington D.C. Metropolitan Area.

INTRODUCTION

Competition for water among governmental entities with common river systems has become increasingly fierce. This competition will no doubt become even more fierce as populations continue to grow and become increasingly dispersed. A classic example of this kind of competition exists in the Washington, D.C., Metropolitan Area where a number of municipal suppliers use the Potomac River as a common resource (4).

"If we took all of the studies that have been done on the Washington area water supply problem and threw them into the Potomac River, we would have a dam." This quoted statement, made by J. J. Corbalis, Jr., Director of the Fairfax County Water Authority (FCWA), one of the institutions competing for water supply in the D.C. area, describes the frustration of many individuals involved in water supply planning in the Washington, D.C., Metropolitan Area (WMA). Frustrations of this kind are liable to grow in other areas of the U.S. when increasing demands for water come up against limited supplies (5).

A major issue in water resource availability is the construction of reservoirs to provide continuous and dependable water supply. Reservoirs require substantial investments in facilities as well as large amounts of land which may be taken out of productive use. Traditional textbook

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(but now outdated) approaches are often based on the Ripple analysis which is used to calculate the safe yield of a reservoir (3). Safe yield is defined as the maximum rate at which water can be withdrawn continuously throughout a specific flow record. The worst drought record is often used for this calculation. One approach would be to meet the monthly deficit by choosing a reservoir whose safe yield is equal to the maximum projected monthly demand. Because monthly demand may not need to be satisfied continuously, this approach is considered quite conservative. Another more refined approach to matching reservoir capacity to projected monthly demand can be obtained by a reservoir operation study. This differs from the Ripple procedure in that computations are based on a specific pattern of varying monthly demands as well as monthly inflows and outflows. A routing procedure essentially determines if the reservoir goes dry during any of the months being tested. In both cases the monthly demands must be adjusted to see if other demands (daily demands for example) are met (11).

Another version of the routing approach is to vary daily flows and demands and to accumulate net deficits over a period of record. The daily and monthly routing procedures are less likely to result in an overbuilt system because demand is matched to supply on a period by period basis. Although in some cases the numerical differences between the three procedures may turn out to be quite small, the daily deficit analysis has particular relevance when one is interested in the timing and "shape" of the deficit. For example, if one is interested in sizing facilities, such as Advanced Waste Treatment Plants, skimming reservoirs or interconnections to meet a short but deep deficit, the timing and "shape" of the deficit to be satisfied is critical.

The concept of using daily deficit flow analysis is suggested in many standard textbooks on water resource analysis (7). Linsley and Franzini provide an example of deficit analysis and its application to the selection of distribution reservoir capacity (8). A similar approach, as described in this paper, was applied to a study conducted on the cost of water supply in the Washington Metropolitan Area (Washington, D.C.). In this study, daily historical flows for 61 yr are matched against actual and projected daily demands for the various purveyors drawing water from the Potomac River in the Washington, D.C., area. Net deficits were used to estimate reservoir capacity. However, it was found that the shape and timing for short-term deficit had a significant impact on the flow augmentation procedures chosen.

The purpose of this paper is to explore the application of deficit analysis techniques for the development of a standardized and meaningful baseline for required water against which various alternatives could be compared. The baseline established for the various alternatives considered was the amount of water required to satisfy deficits based on historical flows and projected demand. These calculations and their usefulness is explored in this paper.

Case Study Area

The Washington Metropolitan Area (WMA) includes the counties of Loudoun, Prince William, Fairfax, and Arlington, and the independent

cities of Alexandria and Manassas Park in Virginia; the counties of Montgomery, Prince Georges, and Charles in Maryland; and the District of Columbia. Within this area there are 25 independent water supply systems ranging in size from less than 1 mgd (3,785 m^3/day) capacity to several hundred mgd capacity. Of these 25, three large water supply facilities exist that furnish about 95% of the total water treatment capacity of the WMA: the Washington Aqueduct Division (WAD), operated by the Army Corps of Engineers, which serves the District of Columbia, Arlington, Falls Church, and part of Fairfax County; the Washington Suburban Sanitary Commission (WSSC), serving Montgomery and Prince Georges Counties; and the Fairfax County Water Authority (FCWA) serving Fairfax County, the City of Alexandria, and part of Prince William County (9).

The problem of assuring an adequate potable water supply to the WMA has been a subject of intense debate for at least 15 yr, and of concern for many more (2). The crucial issue is the growing reliance on the Potomac River as a source of drinking water for the WMA. Under most flow conditions, the volume of water in the Potomac River far exceeds present or projected needs. However, because the river flow is unregulated and is subject to extreme fluctuations over short time periods, concern exists that water supply shortages may result from the simul-

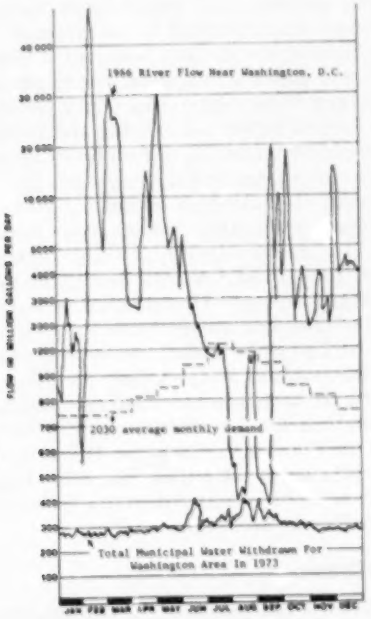
1966 River Flow Near Washington, D.C.
2030 average monthly demand
Total Municipal Water Withdrawn For Washington Area In 1973

FIG. 1.—Hydrograph of 1966 Potomac Flow near Washington, D.C., versus 1973 Municipal Withdrawal and Projected 2030 Average Monthly Demand

taneous occurrence of a maximum water demand period and a low flow period.

Fig. 1 shows the problems of depending on the Potomac River for water supply. The figure shows the 1966 flow (lowest flow of record) of the Potomac, using the Point-of-Rocks river gage versus WMA 1973 total water withdrawals and the projected 2030 monthly demand (10). The Point-of-Rocks gage, which has data back to 1900, is the closest reliable streamflow measuring device on the Potomac upstream of the WMA water supply intakes. The peak demand for water in 1973 was actually greater than the low flow of the river in 1966. The projected 2030 monthly demand far exceeds the 1966 river flow. From this comparison, if demand for Potomac water increases, future shortages could occur.

Potomac River Basin

The Potomac Basin drains an area of 14,669 sq mile (38,000 km^2): 5,720 sq mile (14,800 km^2) in Virginia, 3,820 sq mile (9,900 km^2) in Maryland, 3,490 sq mile (9,000 km^2) in West Virginia, 1,570 sq mile (4,100 km^2) in Pennsylvania, and 69 sq mile (179 km^2) in the District of Columbia (12). The U.S. Geological Survey maintains many gaging stations on the nontidal portion of the Potomac River and its tributaries. The gages immediately applicable to this study are at Point-of-Rocks, Maryland, the station just above the WMA intakes and at Little Falls. Additional gages used in the analysis are those on Seneca Creek, Difficult Run, and the Monocacy River, which are tributaries to the Potomac. Reliable data have been generated at Point-of-Rocks since 1895 and at Little Falls since 1930, but data from the other gages are variable. The Point-of-Rocks gage measures flow prior to any Washington area water withdrawals, while the Little Falls gage is located below the existing and proposed intakes. The difference between the two, after correction for diversion, represents the contribution of local tributaries and direct runoff (6).

Data from the Point-of-Rocks gage indicate a wide variation in flow conditions. The minimum monthly average flows have ranged from 706 cfs (456 mgd − 17.3 × 10^5 m^3/day) in October 1931 to 5,400 cfs (3,490 mgd − 13.2 × 10^6 m^3/day) in March 1931. Low flows have been recorded in all months from July through December. The standard deviation of the monthly flows indicates that the river flows are also extremely variable.

A key feature in utilizing the deficit analysis approach is supply estimation. To estimate available water supply just above the WMA area, flows from all of the tributaries were calculated and a relationship was developed that provided total available supply above the gages as a function of flow at the Point-of-Rocks gage. This relationship will be reviewed in more detail later in the paper. The other important feature of calculating a deficit analysis is water demand estimation. This issue is considered in the following section.

Future Supply and Demand

Demand Projections.—For purposes of this analysis the actual and projected population and employment growth figures for the area were combined with residential per capita and per employee water demand to estimate total water demand for the WMA. Population and employ-

TABLE 1.—Water Usage Scenario

Scenario (1)	Change in water use over 10-yr period (2)
1	Growth in per capita and per employee water usage over entire WMA of 10%
2	Growth in per capita and per employee water usage over entire WMA outside of D.C. of 10% but a decrease of 5% per capita and per employee use in D.C.
3	Maximum growth in per capita and per employee water usage over entire WMA of 5%
4	No growth in per capita and per employee water usage over entire WMA; current use assumed constant
5	Decrease of 5% per capita and per employee use in D.C., and constant (no increase) use elsewhere in D.C. area
6	Decrease of 5% per capita and per employee use over entire WMA

ment figures were based on Corps of Engineers projections (9). Several scenarios were hypothesized which are summarized in Table 1. These scenarios ranged from a growth in per capita and per employee water use of 10% per 10-yr period to a decrease of 5% per capita and per employee per 10-yr period (1978 is used as a base).

Fig. 2 shows the resultant change in Potomac demand for the six different scenarios. As can be seen from Fig. 2, relatively minor increases in water consumption can cause major increases in demand on water resources in the WMA area. Scenario 4 is the one most consistent with the U.S. Army Corps of Engineers study published in 1979 (9). These curves are based on the assumption that the existing sources in the WMA supply a steady yield of 121 mgd (458,000 m^3/day). Table 2 shows pro-

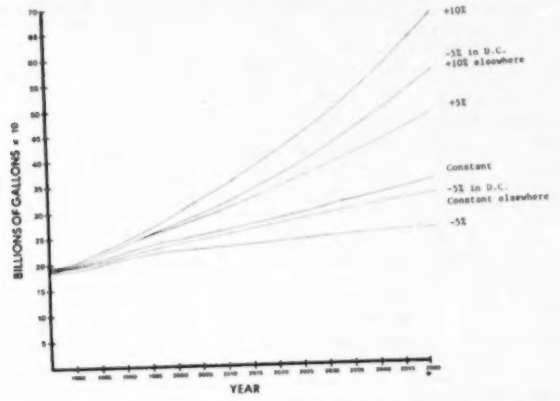

FIG. 2.—Future Water Use (Percentage Changes Are over 10-yr Period) Under Different Water Demands

TABLE 2.—Projected Annual Requirements for Revenue-Producing Water, in Millions of Gallons per Year (Based on Scenario 4)[a]

Area (1)	1976 (2)	1980 (3)	1985 (4)	1990 (5)	1995 (6)	2000 (7)	2005 (8)	2010 (9)
Washington	47,199	49,687	51,965	53,569	55,812	57,752	59,816	61,738
(MGD)	129	136	142	147	153	158	164	169
Virginia	40,603	45,681	51,732	57,789	63,313	67,549	71,166	75,238
(MGD)	111	125	142	158	173	158	199	206
Maryland	42,874	46,228	52,324	58,633	64,321	68,842	73,839	78,418
(MGD)	117	127	143	161	176	189	202	215
Total RPW[b]	130,676	141,596	156,021	169,991	183,446	194,143	204,821	215,394
(MGD)	357	388	427	466	502	532	561	590
Area	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Washington	63,659	65,509	67,359	69,209	71,149	73,035	74,921	76,807
(MGD)	174	179	185	190	195	200	205	210
Virginia	79,798	83,555	88,949	93,443	98,349	102,838	107,187	111,571
(MGD)	219	229	244	256	269	282	294	306
Maryland	82,920	86,175	91,347	95,092	98,855	103,245	107,608	111,997
(MGD)	227	236	250	260	271	283	295	307
Total RPW	226,377	235,239	247,655	257,744	268,353	279,118	289,716	300,375
(MGD)	620	644	679	706	735	765	794	823

[a]To convert from mil gal/yr and mgd to m^3/yr and m^3/day multiply by 3,785.
[b]RPW is the revenue producing water for a utility.

jected water requirements by major area for scenario 4 (constant water use). The water figures shown are based on revenue producing water for the utility. Revenue producing water is the amount of water from which a utility derives its revenue. Table 3 shows various peaking requirements for all of the water users based on the average monthly use and peaking ratios developed for the individual utilities. In this table

TABLE 3.—Washington Metropolitan Area Water Demand,

Item (1)	1976 RPW[b] (2)	1976 RW[c] (3)	1980 RPW (4)	1980 RW (5)	1985 RPW (6)	1985 RW (7)	1990 RPW (8)	1990 RW (9)
Average month	358.0	435.3	387.9	471.7	427.5	519.8	465.7	566.3
Peak month	413.8	503.2	448.4	545.3	494.1	600.8	538.3	654.6
Peak 7 days	475.4	578.7	515.7	627.1	568.2	691.0	619.1	752.8
Peak 1 day	529.7	644.1	574.0	698.0	632.5	769.1	689.1	837.9
Item	**2015 RPW**	**2015 RW**	**2020 RPW**	**2020 RW**	**2025 RPW**	**2025 RW**	**2030 RPW**	**2030 RW**
Average month	620.3	754.2	664.5	783.7	678.6	825.1	706.2	858.7
Peak month	721.1	878.0	750.9	913.0	791.2	962.0	824.1	1,002.0
Peak 7 days	824.6	1,002.6	856.7	1,041.7	902.1	1,096.8	938.8	1,141.0
Peak 1 day	917.8	1,115.9	953.6	1,159.5	1,004.0	1,220.8	1,044.9	1,270.5

[a]To convert from mgd to m^3/day multiply by 3,785.
[b]RPW is revenue producing water for a utility.
[c]RW is raw water pumped by the utility.

both the revenue producing water and raw water requirements are given. Line 1 of Table 3 shows the average monthly use based on the annual requirements listed in Table 2.

The peak monthly demand for raw water in 2050 is expected to reach 1,180 mgd, which exceeds six of the minimum monthly flow recorded at the Point-of-Rocks gage. This disparity between projected demand and historical flow illustrates the problem that may ultimately face Potomac River water users.

Supply Projections.—As mentioned earlier, the most reliable river gage in the D.C. area is the Point-of-Rocks gage, several miles upstream from the WMA inlets. However, four streams enter the Potomac just above the WMA but below the Point-of-Rocks gage. The contribution of these four streams to the flow of the Potomac was estimated and added to the total Potomac flow.

Estimates for the flow from these streams was made based on data available at the gage nearest to the streams' confluence with the Potomac. The flows in the months July through December for the years 1930, 1932, 1944, 1948, 1964, 1965, and 1966 were examined for each gage. These time periods were used because they were the low flow years of record for the Point-of-Rocks gage. The date of low flow for the Point-of-Rocks gage was established for the months July through December for the given years. The corresponding flow was determined for each of the other four gages. Each of the flows for the four tributary streams was multiplied by a factor to account for the additional drainage area in estimating the flow at the stream confluence with the Potomac.

A regression equation was developed to convert Point-of-Rocks flow into total flow available above the WMA intake taking into account the contribution of the four tributaries. In this regression equation, Potomac flow was the independent variable and total flow flow was the dependent variable. The resulting equation that converts flow in cubic feet per

in Millions of Gallons per Day, by Category[a]

1995		2000		2005		2010	
RPW (10)	RW (11)	RPW (12)	RW (13)	RPW (14)	RW (15)	RPW (16)	RW (17)
502.6	611.2	531.9	646.8	561.2	682.4	590.2	717.0
581.0	706.4	614.8	747.6	651.4	792.0	685.9	834.0
668.1	812.4	707.1	859.8	746.0	907.1	784.6	954.0
743.6	904.3	787.0	957.0	830.3	1,009.6	873.3	1,061.8
2035		2040		2045		2050	
RPW	RW	RPW	RW	RPW	RW	RPW	RW
724.2	880.5	753.2	915.8	782.8	951.8	811.7	987.0
805.2	1,052.0	900.6	1,095.0	935.1	1,137.0	970.5	1,180.0
962.7	1,170.5	1,001.2	1,217.4	1,040.6	1,265.3	1,079.0	1,312.0
1,071.5	1,302.7	1,114.4	1,355.0	1,158.2	1,408.3	1,201.0	1,460.3

second at the Point-of-Rocks gage to millions of gallons per day above the WMA intakes is as follows:

$$Y = 0.646\,(0.7976\,Q^{1.052})(r^2 = 0.99) \quad \ldots\ldots\ldots\

continuous period of days with deficits. For each deficit period, the total deficit in cubic feet was totaled. All the deficit periods in a year were identified by their beginning and ending dates and the total annual deficit was summed from all the individual deficits. As will be analyzed later, deficit timing and shape is very important. Two reports were generated: one report listed future deficits based on flows in past years, and the second created histograms that provided a display of the deficit data.

The effect of peak demands on water availability was also examined to assess the worst possible conditions that the WMA might experience. The average month's water demand was multiplied by a factor that translated the average months demand into a maximum one day demand (4). No allowance was made for the reduction in demand that might occur under drought conditions.

For each deficit period the peak deficit is identified as the day that experiences the greatest deficit in the entire deficit period. The lowest daily flow is subtracted from the peak day to provide an estimate of possible short-term deficits.

Results of Analysis

In this section some of the implications of using a deficit analysis approach in designing water supply augmentation facilities are analyzed. Total annual deficits provide information on required flow augmentation capacity, although the values obtained using the approach described earlier will most likely yield results similar to the Ripple or monthly routing procedures. Fig. 4 shows total deficits for simulated 2030 and 2050 demands versus various historical streamflow. For example, the total difference between daily 2030 demand and the 1930 historical flow is approximately 40,000 mm gal, and the difference between daily 2050 demand and the 1930 flow is approximately 70,000 mm gal. As can be seen from Fig. 4, the three years with the largest deficits were 1930, 1966, and 1932.

The number of yearly deficits was found when comparing historic flow against demand estimated for 1980 through 2050 using scenario 4. When 1990 demand is compared against 61 yr of historical record, approximately 17 yr of the record show a deficit. Using the 2050 demand, 50 yr have deficits and nearly 300 deficit periods occur. A deficit period

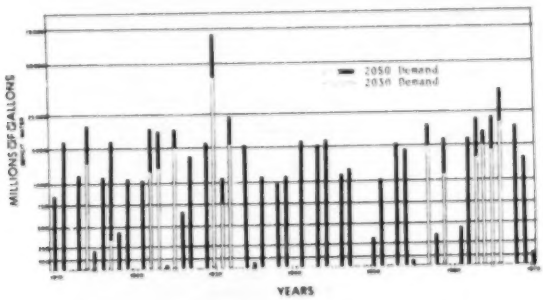

FIG. 4.—Deficit Flow History Based on 2030 and 2050 Estimated Demand

TABLE 4.—Projected Total Deficits,* in Millions of Gallons per Year

Year (1)	Based on 1930 river flow (2)	Based on 1966 river flow (3)	Based on 1932 river flow (4)
2000	11,615	5,586	855
2005	16,356	7,603	1,703
2010	21,322	9,949	2,578
2015	26,895	12,482	3,552
2020	31,595	14,512	4,984
2025	38,235	17,382	7,043
2030	43,736	20,089	9,067
2035	50,692	23,584	12,067
2040	56,725	26,657	14,842
2045	62,686	29,833	17,562
2050	68,768	33,029	20,394

*To convert from mgd to m^3 multiply by 3,785.

begins whenever the available water becomes less then the demand for raw water and ends when it becomes greater again. Several deficit periods may occur in a single year. The probability of having a severe deficit increases dramatically as demand increases. Table 4 shows the magnitude of the yearly deficits based on 1930, 1966, and 1932 flows. The probability of deficits occurring in the future is high. Based on the stated assumptions, the probability of having a large number of deficit periods in a given year increases as demand increases.

Another approach to using the annual deficit data is to calculate the probability of occurrence of a given deficit. Fig. 5 shows the return period for annual deficits as based on the 2030 and the 2050 simulated demands and the 61 yr of daily flow records. According to Fig. 5, a 25,000 mm gal deficit represents approximately a 50 yr return period for the 2030 demand, and a 20 yr return period for the 2050 demand. Note that there appear to be three separate distributions for the deficit data. The tangent to the far right appears to represent an extreme value distribution. Total deficits can provide very useful information but the def-

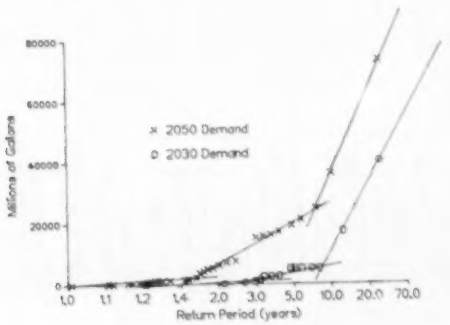

FIG. 5.—Return Period for 2030 and 2050 Annual Deficits

icit pattern and timing can also provide extremely useful data.

Deficit Pattern and Timing.—Figs. 6–7 show the deficit position in time for the 1966 and 1930 river flows against 2030 and 2050 demand conditions. As can be seen for the 1966 flow, the deficit for June through December is greater than the surplus, but some surplus does occur between deficits. For the 1930 flow conditions, almost no surplus occurs. The deficits in 2050 become deeper and last for a longer period of time compared to those in 2030. These figures show that the shape of the deficits may be important in solving water shortage problems. For the 1966 river flow condition, deficits are of short duration, but deep. For 1930 river flow conditions deficits are long and relatively shallow. Therefore, any facilities built to alleviate the 1966 shortage will require a large peaking capacity and will have to operate over a short time period. For the 1930 condition, deficits could be satisfied by facilities with lower peaking capacity but capable of operating over a longer time period. The deficit analysis therefore also reveals important information about the

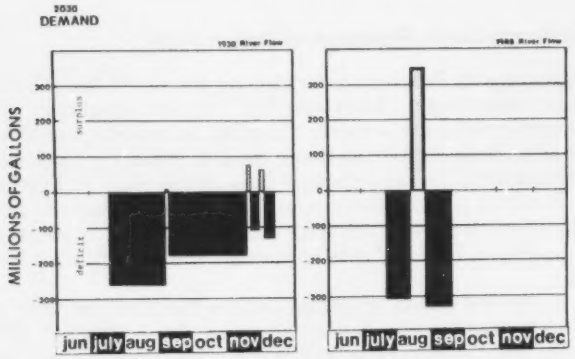

FIG. 6.—Location of Deficits in Time (2030 Demand)

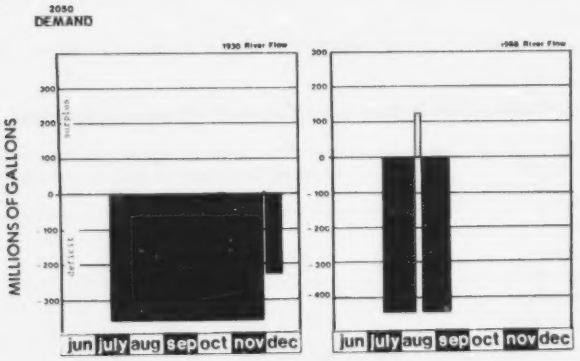

FIG. 7.—Location of Deficits in Time (2050 Demand)

kind of water shortages that might occur in the WMA. These deficit patterns may have an impact on the kind of solution that might be tried to alleviate shortages in the WMA.

Based on this analysis and assuming constant per capita use and the projected population growth, water shortages are expected to occur with increasing frequency. They may or may not be of sufficient size or duration to warrant immediate action. If they are severe, however, the types of facilities designed to meet them may be critical. For example, some deficits may require that large quantities of water be available for short periods of time, while other deficit patterns will be satisfied by smaller quantities of water available over longer periods of time.

The previous analysis dealt with totally unregulated Potomac flow. Fortunately, action has been taken to forestall immediate water shortages by construction of the Bloomington Reservoir, which is considered in the following section. This analysis will illustrate the sensitivity that deficit analysis displays for analyzing the impact of supply agumentation facilities.

Effect of Bloomington Reservoir on Deficit Flow

The Bloomington Reservoir is located on the North Branch of the Potomac near Bloomington, Maryland (1). The flow regulating properties of this reservoir will have a significant effect on water availability during low flow periods in the WMA. Based on U.S. Army Corps of Engineers (COE) assumptions, it can release a flow of 135 mgd (511,000 m^3/day) into the Potomac for 120 continuous days. To illustrate the effect that the Bloomington Reservoir will have on alleviating water shortage problems in the WMA, the COE release patterns shown in Table 5 have been assumed.

Fig. 8 shows the newly projected deficits for 2030 and 2050 demand versus historic river flows. A comparison of Fig. 8 with Fig. 4 immediately shows that the Bloomington Reservoir will greatly reduce the number and potential severity of deficits in the WMA. Tables 6–7 show the effect that the Bloomington Reservoir will have on the magnitude and size of deficit over time, assuming 1930, 1966, and 1932 river flow conditions.

The availability of water from the Bloomington Reservoir will ob-

TABLE 5.—Potomac Flow Augmentation (Corps of Engineers), Bloomington Planned Release[a]

Month (1)	Quantity, in millions of gallons per day[b] (2)
July	60
August	135
September	135
October	135
November	75

[a]Plus 2-day storage in existing water system.
[b]To convert from mgd to m^3/day multiply by 3,785.

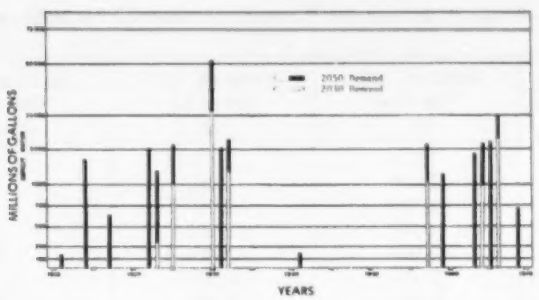

FIG. 8.—Deficit Analysis with Bloomington Reservoir on Line (2030 and 2050 Demand)

viously reduce the potential severity of the short and long-term water supply shortages in WMA. Significant deficits may still occur, and as population and demand grow, the probability of a deficit condition increases. Construction of the Bloomington Reservoir has probably delayed these occurrences until a later stage in the planning period.

This analysis clearly demonstrates the impact that a single reservoir can have on flow patterns in the Potomac basin.

Optimizing Bloomington Release Pattern.—The discharge pattern shown in Table 5 is planned for low flow conditions; however, if the discharge pattern could be managed in real time to match actual river flow conditions, the Bloomington capacity could be used even more efficiently, thereby delaying any future construction. Unfortunately, coordinating release patterns at Bloomington with flow conditions 30 days travel time downstream is not easy. It might be possible to monitor the situation and use simulation models to provide an early warning alert that levels of flow are about to drop below demand. Such an effort would appear worthwhile in this case. Perhaps additional water beyond that normally designated for water supply could also be released under extreme low flow conditions.

Hypothetically, if the releases from Bloomington could be timed to low deficit conditions in the WMA, the effect of Bloomington release patterns on the construction date for the first new reservoir would be as shown in Table 8. In this case the historical flows for 1930, 1966, and 1932 were compared against simulated demand using scenario 4. By matching the total available yield as shown in Table 5 against the deficit patterns for the three critical years of 1930, 1966, and 1932, the "optimal" release pattern was determined. In this "optimal" release pattern the timing of the release was assumed to match exactly the deficit pattern for a given year. When the total yield could no longer provide a sufficient volume of water to meet the deficit, it was assumed that another flow augmentation alternative was required. Table 8 summarizes these calculations.

As demonstrated in Table 8, an optimal release pattern under moderately severe low flow conditions (1932 flow) could delay additional reservoir or additional flow augmentation construction from 2011 to 2035.

TABLE 6.—Projected Deficits with Bloomington Reservoir,[a] in Millions of Gallons per Year

Year (1)	Based on 1930 river flow (2)	Based on 1966 river flow (3)	Based on 1932 river flow (4)
2000	196	620	0
2005	2,100	2,100	0
2010	6,500	3,800	0
2015	11,390	5,650	190
2020	15,840	7,400	860
2025	22,400	10,300	1,900
2030	27,800	12,600	2,700
2035	34,600	15,650	4,160
2040	40,700	18,700	6,000
2045	46,600	21,900	8,500
2050	52,600	25,100	11,200

[a]To convert from mil gal/yr to m^3/yr multiply by 3,785.

TABLE 7.—Peak Deficit, in Millions of Gallons per Day, with Bloomington Reservoir[a]

Year (1)	Based on 1930 river flow (2)	Based on 1966 river flow (3)	Based on 1932 river flow (4)
2000	50.0	119.0	0
2005	114.3	155.8	0
2010	116.0	204.8	0
2015	150.7	242.4	90.5
2020	185.9	254.0	146.0
2025	236.3	279.9	156.2
2030	268.1	330.6	193.4
2035	260.2	368.7	245.2
2040	298.7	385.5	290.9
2045	324.9	426.6	311.8
2050	362.2	447.9	361.5

[a]To convert from mgd to m^3/day multiply by 3,785.

Note: Peak deficit of greater than 7 days duration that occurred during the year indicated.

Optimal release occurs when the actual amount of deficit water is released from the reservoir at the proper time so that the released water is at the water utility intake when needed to supplement the amount of supply water that would have been available if the release had not occurred. This is difficult to achieve, but a compromise release pattern somewhere between the planned and optimal pattern should be possible.

Additional analysis comparing daily deficit pattern based on historical river flows and projected demands revealed that the timing and shape of the deficits was such that the use of flow augmentation devices such as advanced waste treatment facilities would be extremely expensive. The deficits could eventually become so deep and last for long periods

TABLE 8.—Effect of Optimal Release Pattern, Year Additional Water Supply Required

Release patterns (1)	Based on 1930 river flow (2)	Based on 1966 river flow (3)	Based on 1932 river flow (4)
Planned release pattern	1996	1996	2011
Optimal release pattern	2003	2020	2035

so that advanced waste treatment facilities would have little flow augmentation impact. The nature of the deficits was such (Figs. 6–7) that an advanced waste treatment plant release would do little to relieve the deficit (4).

This paper demonstrates a procedure for calculating deficits and attempts to point out the usefulness of knowing deficit timing and pattern. From this analysis it is obvious that the deficit flow analysis approach can be used to accurately size facilities such as reservoirs for flow augmentation. Not only can the magnitude of the deficits and their frequency of occurrence be estimated, the shape of the deficit can be predicted as well. This information can be extremely useful for designing flow augmentation options. By using this approach and assuming that the Bloomington reservoir release patterns could be matched against projected deficits, this facility could reduce significantly projected deficits even beyond the reductions shown.

Summary and Conclusions

The traditional approach to estimating required reservoir capacity is to compare the highest water demands in the area to the lowest flows in the stream or river being considered as a water source. This approach can lead to overestimates of the magnitude of reservoir capacity required. A deficit analysis approach matches available flow versus actual or projected demands, or both.

The deficit analysis approach accounts for the dynamic nature of supply and demand conditions. A computer program has been developed to provide for the day by day historically available flows versus projected demands. This technique should provide for more careful and precise analysis of reservoir capacity requirements and for the capacity requirements of other flow augmentation facilities.

Appendix.—References

1. Aspinwell, R., Daley, S. A., and Phillipe, J. T., "The Optimization of Raw Water Interconnects for the Washington, D.C. Metropolitan Area, Phase I: Hydrologic and Hydraulic Data," Prepared by GKY and Associates, Inc., Alexandria, Va. for the U.S. Army Corps of Engineers, Baltimore District, Md., June, 1979, pp. 111–117.
2. Aurand, D., Gordon, Y., Amr, A., Boberschmidt, L., Saari, S., Persons, G., and Myhra, D., "Draft Environmental Impact Statement Concerning Proposed Potomac River Water Supply Structures," prepared by the U.S. Army Corps of Engineers, Baltimore District, with Assistance of METREK Division

of the MITRE Corporation, 1820 Dolly Madison Blvd., McLean, Va., MTR 7578, 1978, pp. 1-2 to 1-3.
3. Clark, J. W., Viessman, W., Jr., and Hummer, M. J., *Water Supply Pollution Control*, A Dun-Donnelley Publisher, New York, N.Y., 1977, pp. 59–69.
4. Clark, R. M., Gillean, J. I., Adams, W. K., and Goodrich, J. A., "Analysis of the Economics of the Water Supply in the Washington Metropolitan Area," EPA-600-12-80-136, Drinking Water Research Division, Municipal Environmental Research Laboratory, U.S. EPA, Cincinnati, Ohio, July, 1980.
5. Crews, J. E., "Planning for Drought: A Management Perspective," *Journal of the Water Resources Planning and Management Division*, ASCE, Vol. 107, No. WR1, Proc. Paper 16078, Mar., 1981, pp. 45–59.
6. "Geological Survey, 1975, Water Resources Data for Maryland and Delaware, Part I, Surface Water Records; Part 2, Water Quality Records," U.S. Department of the Interior, Washington, D.C., 1974.
7. James, L. D., and Lee, R. R., *Economics of Water Resources Planning*, McGraw-Hill Book Co., Inc., New York, N.Y., 1971, pp. 287–294.
8. Linsley, R. K., and Franzini, J. B., *Water Resources Engineering*, McGraw-Hill Book Co., Inc., New York, N.Y., 1979, pp. 150–157.
9. "Metropolitan Washington Area Water Supply Study for the Potomac River User; Progress Report," Department of the Army, Baltimore District, Corps of Engineers, Aug., 1979, pp. 2–3.
10. "Northeastern U.S. Water Supply (NEWS) Study; Washington Metropolitan Area Water Supply Study," Department of the Army, North Atlantic Division, Corps of Engineers, Nov., 1975, p. 10.
11. "Northwestern U.S. Water Supply Study, Washington Metropolitan Area Water Supply Study, Annex B Water Supply, Demand and Deficits," Department of the Army, North Atlantic Division, Corps of Engineers, Nov., 1975, pp. 41–43.
12. Sheer, D. P., "A Perspective on the Washington Metropolitan Area Water Supply Problem," Interstate Commission on the Potomac River Basin, 814 East West Towers, 4350 East West Highway, Bethesda, Md., May, 1977.

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